Preface

"Remote sensing" is already an essential tool for many Earth and planetary scientists, whether they are studying the atmosphere, the land, the ocean floor, or the surface of the planet Mars. The analysis of active volcanic processes is one such discipline where there has been a recent dramatic increase in the diversity and capabilities of remote sensing. But the use of remote sensing data, collected either from a satellite or from an aircraft, requires different technical skills to obtain, process, and interpret the data, which is different than the well established field-oriented approach. Thus, this book fills a need for a single compilation of remote sensing results for volcanoes, along with appropriate tutorials and background information, which will stimulate greater interaction between the image analyst and the field volcanologist.

This volume therefore provides the first compilation of the many diverse remote sensing techniques that are being applied to the study of active volcanoes. The chapters cover a broad segment of the electromagnetic spectrum, and bring together many of the diverse techniques that have been used to study active volcanism. These methods range from ultraviolet observations of sulfur dioxide in the stratosphere to the use of active lidars measuring the deformation of a caldera, and the determination of the thermal energy of a lava flow from thermal infrared measurements. Experimental field techniques are also described, including the measurement of volcanic gas ratios using Fourier transform infrared spectroscopy. By virtue of this broad range of techniques and study areas, the volume is likely to appeal to a wide range of scientists, hazard mitigation professionals, and educators. The field volcanologist will also find this volume to be stimulating by virtue of the detailed studies of infrequently studied volcanoes in remote parts of the world. Significant new information can be obtained using satellite remote sensing, and this volume includes analyses of volcanoes in the Grand Comores Islands, Kamchatka, and the Galapagos. Operational agencies who have the mandate to detect and provide warnings about volcanic ash clouds, as well as surface activity, will also benefit from reading this volume. Atmospheric scientists interested in using volcanic ash as a tracer for 4-D circulation models, or the determination of the abundance and distribution of volcanic gases in the atmosphere, will find this book useful. Finally, it is expected that many of the results presented here will be of value to upper level undergraduate or to graduate-level courses, particularly because the chapters provide a multi-sensor approach to the analysis of a single geologic process.

Several innovative aspects of remote sensing in volcanology are presented in this volume. The ability to collect, process, and display data from geostationary satellite within minutes of image acquisition is reviewed. This web-based volcano thermal anomaly detection technique promises to radically change the way that certain volcanoes are monitored as data sets can be automatically obtained every 15 – 30 minutes, day or night. Establishing strong collaboration between the remote sensing community and volcano observatories is highlighted by the new capabilities that such monitoring techniques now enable. This volume also provides the first comprehensive summary of volcano deformation around the world as determined by the rapidly developing technique of radar interferometry. Future sensors dedicated specifically to these methods are already being discussed by several government agencies, so that the material described here can serve as a basis for reviewing the successes and limitations of these methods on different volcanoes.

This volume derives from four special sessions that were presented at the Fall 1997 American Geophysical Union meeting in San Francisco. While several papers included here document the findings presented at that meeting, several chapters include rapidly developing ideas and discoveries that have been developed since that time. Additional materials, such as the background to the constraints imposed on obtaining satellite data due to the orbit of the spacecraft, are also included here to provide a comprehensive review. The compilation of papers is particularly timely by virtue of the new fleet of Earth-orbiting sensors that will soon be used to study volcanoes. Over the next couple of years, highly capable instruments will be placed into orbit by the United States, Europe, Canada and Japan. As has been proven in the past, remote sensing specialists with a particular interest in volcanoes are likely to develop innovative new ways to utilize these observations in the analysis of eruptions. This volume therefore stands as a compilation of what has already been accomplished, and points the way forward in many aspects of the discipline. Individuals intending the enter this new era of volcano studies, as well as investigators already in the field who wish to learn more about the diversity of techniques, are sure to find much of interest within this volume.

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Introduction to Monograph

Volcanic eruptions are spectacular but dangerous phenomena to study up-close, and present many challenges because of the diversity of activity and their remote locations. The tragic loss of life at Galeras and Mt. Unzen volcanoes in the early 1990's illustrates the dangers associated with studying active volcanoes at close quarters (Kerr, 1993; Baxter and Gresham, 1997). Partly in response to these challenges, remote sensing techniques have been developed to enable a volcanologist to make quantitative observations of active volcanic processes at a safe distance. These techniques draw upon many diverse disciplines, and frequently include expertise from communities outside of volcanology and the Earth sciences. Using methodologies originally developed for the exploration of other planets, sensors now flown in Earth orbit and on aircraft can contribute to the study of volcanoes for hazard mitigation and response, as well as contribute to the basic understanding of volcanic processes. This Monograph assembles a collection of 13 papers to show that useful remote sensing observations of eruptions can now be made that will enhance the more established field studies of volcanoes, and provides the volcanologist with an introduction to this evolving discipline.

Much progress has been made in the field of volcano remote sensing during the decade of the 1990's, and further substantive developments are to be expected over the next few years as next-generation spacecraft are launched by the United States, Europe, Canada, and Japan. At the time of writing, the Landsat 7 spacecraft is poised to become an operational Earth observatory, with a long term plan for the acquisition of data for all of Earth's land surface on a routine basis (Goward et al., 1999). The next U.S. spacecraft called "Terra", which is the first part of the Earth Observing System (EOS), is planned for launch in late 1999. Research into the volcanological uses of EOS data has been conducted for almost a decade (Mouginis-Mark et al., 1991), and similar preparations have been made for the use of other remote sensing data. For instance, Landsat 7 and Terra will be joined in the next few years by the highly capable Environmental Satellite (ENVISAT) and the Advanced Earth Observing Satellite 2 (ADEOS II) spacecraft, flown by Europe and Japan respectively. Both ENVISAT and ADEOS II carry visible- and infrared-wavelength sensors, and ENVISAT will also have an imaging radar system. Dedicated imaging radar missions, such as RADARSAT 2 and the Advanced Land Observing System (ALOS), will be flown in the 2001 – 2004 timeframe by Canada and Japan, respectively.

Earlier reviews of satellite remote sensing of volcanoes (e.g. Francis, 1989; Mouginis-Mark and Francis, 1992; Mouginis-Mark et al., 1993; Rothery and Pieri, 1993; Self and Mouginis-Mark, 1995; Francis et al., 1996; Sparks et al., 1997; and Oppenheimer, 1998) have tended to focus on individual sensors, wavelength regions, or techniques. This Monograph provides insight into the many different aspects of volcanology that the remote sensing community is investigating the geographic areas currently being studied, and the different instruments that they will use in the coming years. Discussions are also included that address the need to develop base-line data sets against which future changes can be measured.

The topics in this volume cover a wide diversity of remote sensing techniques and different volcanoes. The Appendices are provided to guide the reader to the relevant techniques and the portions of the electromagnetic spectrum which are used for these studies. A listing of each volcano discussed in the volume is also provided as an appendix. While each contributed paper is focused on a single aspect of remote sensing in volcanology, there are several related themes. Obviously, each volcano has a unique history of activity, which can include explosions that produce giant ash clouds, the eruption of lavas over time periods ranging from hours to more than a decade, or the release of large quantities of volcanic gases such as sulfur dioxide into the atmosphere. Ground deformation is also a frequent characteristic of an eruption, either as a consequence of subsurface magma transport or an eruption. Some of these styles of activity can also pose a hazard to people and property on the ground and, in the case of eruption plumes, may also threaten the thousands of jet aircraft that annually fly air routes that cross over volcanic regions such as the Alaska Peninsula. Development of computer models that predict the dispersal pattern of the ash (e.g., Searcy et al., 1998) will rely on accurate and timely observations of the plume. All of these attributes can now be studied at some level using remote sensing.

Some aspects of the remote sensing of volcanoes are not covered in this Monograph, because they do not involve on-going eruptions, or they have been described in earlier reviews. An important early use of satellite data in volcanology involved the basic mapping of landforms. The analysis of Landsat Thematic Mapper images for extensive parts of the South American Andes (de Silva and Francis, 1991) provided new insights into the volcanology and tectonics of this infrequently studied region. Compositional mapping of lava flows using thermal infrared images (Kahle et al., 1988) has also aided the analysis of volcanoes such as Mauna Loa, Hawaii. Similarly, radar images have been used for mapping of volcanic flows and structures (e.g., Gaddis, 1992; Rowland et al., 1993; Chorowicz et al., 1997), as well preliminary studies of remote volcanic islands (Garvin et al., 1999). Here the all-weather and day/night imaging capabilities of the different orbital radar systems provided image data that could not be obtained by optical sensors due to cloud cover.

This Monograph also does not consider some of the effects of volcanic eruptions on the upper atmosphere. Particularly in the case of the 1991 eruptions of Mt. Pinatubo, there were extensive measurements made of the chemistry, particle size distribution, and dispersal pattern of the plume (e.g., McCormick and Viega, 1992; Read et al., 1993; Ackerman and Strabala; 1994). Spacecraft that observed the edge of the Earth's atmosphere (referred to as "limb-sounders") were able to obtain vertical profiles through the atmosphere to measure the SO_2 abundance and aerosol optical depth as a function of time after the eruption. In essence, the Mt. Pinatubo plume provided the tracer for testing stratospheric circulation models. The changing chemistry of the stratospheric aerosols over a period of many months after the eruption was of more importance to the analysis of ozone depletion than to predicting the fall-out of ash or the impact of the eruption on hapless aircraft encountering the plume.

There are other more innovative remote sensing methods that also pertain to the analysis of volcanic eruptions not included in this volume. The Global Positioning System (GPS) is finding an array of uses in addition to the location of ground positions and ground deformation on volcanoes. Experiments are currently under way to use real-time GPS measurements to infer water vapor concentrations in the atmosphere, and it is probable that similar efforts could be made to infer the structure of an eruption plume if the GPS array can be positioned in the field sufficiently rapidly. Acoustical techniques for studying the harmonics of gas rising within an active conduit have been initiated by Garces and Hansen (1998). These data provide startling information on the geometry of the active conduit, and so may evolve into an essential remote sensing system for monitoring dynamic changes within the shallow layers of an active volcano. Clearly, such acoustical methods could never be adapted to be part of a spaceborne system due to the vacuum of the space environment, but airborne observations (perhaps from long duration pilot-less aircraft) could be deployed to remotely study dynamic changes on an active volcano. Finally, potential field measurements could be used to study active volcanoes. At the present time, gravity and magnetic observations have to be made from aircraft because the spatial resolution of spaceborne sensors is of the order of a few hundred kilometers, and so cannot be applied to individual volcanoes. However, progress in the development of multiple spacecraft flying in close formation with each other (e.g., NASA's Gravity Recovery and Climate Experiment; GRACE, due to fly in 2001) may someday improve the sensitivity of spacecraft observations to permit the study of volcanic eruptions.

Descriptions of Papers

This Monograph is arranged into four main sections, dealing with remote sensing studies of volcanic plumes, volcanic gases, thermal activity, and ground deformation and topography of volcanoes. These sections are prefaced by the chapter by Mouginis-Mark and Domergue-Schmidt, who review the constraints that the satellite orbit and the sensor field of view place on the acquisition of data for volcanoes. It is often assumed that the satellites are obtaining data continuously, and that an image can be obtained within a few hours or days after an eruption is identified on the ground. Far from being an easy task, these authors show that obtaining remote sensing data over a particular volcano may take weeks, and sometimes months, to accomplish. This may be due to the need for special programming of the satellite, potential cloud cover over the area of interest, and the slow delivery schedules for data received at foreign ground stations. The special data requirements for measuring ground deformation and topographic change via radar interferometry are also introduced.

Section 1 contains four papers on the identification, analysis and tracking of volcanic plumes. Krueger and colleagues review the 20 years of observations of volcanic sulfur dioxide that have been made with the series of Total Ozone Mapping Spectrometer (TOMS) instruments. These instruments have produced the best consistent long-term data set on stratospheric sulfur dioxide since 1978, and in certain instances the TOMS data have been used to identify the source volcano for volcanic plumes (Krueger et al., 1996). The TOMS data provide insights into the removal rates of sulfur dioxide from the atmosphere, interactions with the co-erupted ash particles, and responses to meteorological conditions. Ash burden in plumes can also be mapped with TOMS, and these results hold interesting implications for petrologists and atmospheric scientists as the observations indicate the existence of a volatile phase in the pre-erupted magma and indirect evidence for co-erupted H_2S gas within drifting eruption clouds.

The combination of TOMS data with another weather satellite instrument, the Advanced Very High Resolution Radiometer (AVHRR), is employed by Constantine and her colleagues to describe the one-week history of the August 1991 eruption clouds from Cerro Hudson volcano, Chile. This study includes the estimation of ash burden, SO_2 abundance, cloud area and maps of cloud distribution. The early detection and interpretation of eruption plumes using satellites has not only scientific importance; plumes form significant hazards to air traffic where the ash may be ingested by jet engines (Casadevall, 1994a, b). To best take advantage of satellite observations, specific protocols between the remote sensing specialists, volcanologists, and the operational agencies such as the Federal Aviation Authority have to be established prior to the eruption. The paper by Schneider and colleagues describes how a communications network has already been developed for the State of Alaska, and they provide examples of how AVHRR, GOES and GMS satellite observations were used to provide warnings during the December 1997 eruption of Bezymianny volcano, Kamchatka.

The final plume study extends the detection algorithms to infer the concentration of sulfate and silicate ash masses in the 1982 El Chichon eruption plumes over the first few days of activity. Yu and Rose present a new model that uses six-band infrared data from the High Resolution Sounder/2 (HIRS/2) instrument, and show how the ash content and effective ash radius of an eruption plume can be monitored over time. The HIRS/2 sensor will soon be joined by the Moderate Resolution Imaging Spectroradiometer (MODIS) that will fly on several NASA spacecraft including Terra, and the technique may yield important new information on the scavenging of effect of ash within a plume and the rate at which sulfate aerosols are removed from the atmosphere.

The two papers on volcanic gases in **Section 2** describe how remote sensing can be used to obtain rates of gas emissions, either by imaging a large portion of the plume from space, or by near-continuous monitoring of the plume via Fourier Transform infrared (FTIR) techniques. Using aircraft data from the Thermal Infrared Multispectral Scanner (TIMS) instrument, Realmuto demonstrates that data collected in the thermal IR portion of the spectrum between 8 – 12 μm can provide quantitative measurements of sulfur dioxide. Comparable data will soon be available from space from MODIS and the Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER), and these data will enable tropospheric sulfur dioxide emissions to be measured several times per year at specific sites.

Love and colleagues take a different approach to measuring gases, describing their FTIR field observations of White Island and Ruapehu, New Zealand, and Popocateptl, Mexico. Retrievals of SO_2, H_2O, HF, SiF_4 and HCl at ranges up to 17 km are presented based on the ground measurements, but most exciting aspect of this work is the potential for this method to be used in space-based observations with imaging FTIRs. They discuss the utility and limitations of FTIR work for future remote measurements of volcanic gases, and conclude that while long-range passive IR spectroscopy works best at high altitude, dry locations, it is still useful for other settings. Already airborne experiments are being conducted (McGee and Gerlach, 1998; Realmuto and Worden, 1998), and space-based observations will be possible from the future NASA Tropospheric Emission Spectrometer (TES). Particularly in cases where satellite observations are made looking directly down on to a hot volcanic target, it should be possible to investigate not only the chemical analysis of volcanic gases, but also to determine the spatial mapping of their sources.

Section 3 presents two studies of the thermal properties of active volcanoes. The high temperatures associated with active volcanoes are easily detectable in the infrared portion of the electromagnetic spectrum (~1 – 12μm). Even when the anomaly dimensions are less than the spatial resolution of the imaging system, the very high radiative energy associated with volcanic thermal features frequently saturates sensors that were originally designed for much lower temperature applications. Lava extrusions at temperatures of ~1000 °C are the most obvious volcanic thermal features that can be studied, but there are many others. These include: fumaroles emitting steam and other gases; pyroclastic flow deposits consisting of hot, solid, fragmented material; columns of ash and gas rising convectively into the atmosphere after explosive eruptions; and lakes of hot water ponded in the craters of active volcanoes. The two thermal papers in this Monograph present complementary reviews of this rapidly evolving field of volcanology. Harris and his coworkers describe the real-time capabilities of low spatial resolution instruments that are flown on weather satellites. The provision of time-series information, sometimes collected as frequently as four times per hour, is used to describe the eruption characteristics of several volcanoes in Central America and Hawaii. In contrast, Flynn and colleagues consider the uses of satellite instruments that have much higher spatial resolution but can only collect data at best only once every week. The Landsat series of spacecraft fall into this category, and there are other instruments such as the Advanced Along-Track Scanner Radiometer (AATSR), and ASTER that will also provide this capability.

Flynn and colleagues also delve into the potential science returns that will be associated with thermal observations made by next-generation instruments that make measurements in dozen (or hundreds) of wavelengths rather than the current sensors (all less than 10 spectral channels). Only field observations of active lava flows have so far been made with these new "hyperspectral sensors". However, the increased sampling and higher dynamic range (which avoids the saturation problems associated with the current spaceborne systems) augers well for more precise measurements of thermal flux, as well as the detection of more subtle thermal anomalies associated with, for instance, active lava tubes.

The fourth section, on ground deformation and volcano topography, relies on the use of imaging radar systems and laser altimeters. Complementary studies using the European imaging radars (ERS-1 and ERS-2), as well as other spaceborne radars, are provided by Massonnet and Sigmundsson, and by Zebker and his colleagues. Ever since the revelation that the phase information in orbital radar images could be used to map the deformation field of the 1992 Landers earthquake in California (Massonnet et al., 1993), radar specialists have been trying to apply this same technique to map the deformation field of volcanoes. As both radar interferometry papers in this volume show, it is then possible to apply inverse modeling techniques to infer the dimensions and geometry of intrusions. Numerous volcanoes have now been studied in this manner, and the two chapters provide a comprehensive summary of the results to date.

Zebker and coworkers also provide a review of the uses of radar interferometry to study surface change on volcanoes. This technique offers considerable potential for the mapping of the growth of lava flow fields, the identification of areas of erosion on ash deposits and pyroclastic flows, or for the analysis of caldera and cinder cone growth.

The uses of radar interferometry are further extended in the chapter by Rowland and Garbeil, who investigate the morphological characteristics of oceanic basaltic volcanoes using digital elevation models (DEMs). They take a longer-term perspective on the period of activity of a volcano, and use elevation data collected by several different remote sensing instruments to study the slope and erosional characteristics of volcanoes in Hawaii, the western Galapagos Islands, Grand Comores Islands, and Reunion Island. Such studies currently rely solely on the one-off analysis of individual DEMs. However, a further quantum step forward in the application of this technique will come when time-series information, in the form of DEMs collected several months or years apart over the same active volcano become available. Already there have been some comparative studies of this type (e.g., Rowland et al., 1999) and they are likely to become more frequent when reference data sets such as that to be collected by the Shuttle Radar Topographic Mission (SRTM) in late 1999 are compared with other DEMs obtained over active volcanoes at other times.

The final chapter is also focused on the collection and analysis of digital topographic data for the detection of ground deformation on volcanoes. Hofton and her colleagues take a different approach to the radar investigations, choosing instead to rely on scanning laser altimeters flown on aircraft to study the Long Valley caldera, California. Here there are significant challenges to be overcome in the form of co-registration of data sets and the removal of possible errors due to motion of the aircraft platform. The reader is provided with insight into the care that must be exercised in the planning of aircraft deployments as well as the inherent problems in comparing data sets obtained from different instruments. Profiles collected from airborne lidars have already proven useful for the documentation and characterization of the topography of other volcanoes (Garvin, 1996), although collecting data outside the United States is often logistically very difficult. Regional coverage will have to wait for the orbital flights of the Vegetation Canopy Lidar (VCL) and IceSAT, which will both fly lidar altimeters in space in the next few years.

Real-time remote sensing observations and community outreach

This Monograph primarily describes the retrospective analysis of satellite and aircraft data collected over active volcanoes. But remote sensing will play a different role when real-time observations become available, as many of the volcanic eruptions seen by spacecraft will have immediate social and economic impacts. A satellite capability called "Direct Broadcast" is already under development, enabling real-time data to become available; care will have to be taken to follow the appropriate agency procedures when contacting the responsible officials (e.g., IAVCEI, 1999). Care should also be taken when press releases are written by remote sensing scientists and agencies such as NASA. The establishment of strong collaborative ties with foreign volcano observatories through joint collection and analysis of satellite data is one method to ensure that local issues remain of paramount importance. Remote sensing interpretations by the remote sensing community should not be released directly to the general public; rather we propose that local responsible volcanologists are the primary people who are informed of the observations. Warnings or forecasts should not be made based on remote sensing data alone. It should be left up to the on-site volcanologist team leader or spokesperson to incorporate the remote sensing information into their decisions and statements.

Satellite remote sensing can yield an improved understanding of volcanic processes simply by providing an enormously enhanced monitoring capability, but it is vital that the data are sometimes validated via observations made on the ground. It can also provide qualitatively different kinds of scientific insights from anything possible previously; literally remote sensing provides new ways of looking at volcanoes. The thirteen papers in this Monograph cover a wide range of topics related to the use of field, aircraft and satellite observations. In many respects, there is an evolution from one type of observation to another. For example, the field measurement of volcanic gases using FTIR data (Love et al., this vol.) can be viewed as a test case for aircraft and space-based observations. Field validation of satellite measurements will be a critical function because an orbital sensor cannot match the spatial resolution of a ground instrument and, for individual field experiments, observations on the ground have much higher temporal resolution. However, the spaceborne thermal volcano monitoring techniques described by in this volume by Harris et al. are rapidly approaching the point where they will become the preferred measurement tool for certain active volcanoes. The aircraft measurements described by Hofton et al. (this vol.) and by Realmuto (this vol.) can also be considered as test experiments that will ultimately lead to space-based observations. In both cases, satellites are currently being built that will fly comparable instruments in the next four years, so it is important to gain practical experience and develop the computer algorithms that can process these future data sets.

Considerable use is already being made of the World Wide Web for the display of satellite data of volcanoes. Public outreach efforts such as the stimulating VolcanoWorld will excite the general public with images and information on volcanoes, including that obtained by satellites. More technical discussions of the uses of remote sensing data are presented by Michigan Technological University's volcanoes web page. The NASA Earth Observing System (EOS) Volcanology Team (Mouginis-Mark et al., 1991) maintains a page focused on the techniques and algorithms that will be used during these up-coming missions. Near real-time satellite observations of the thermal properties of several volcanoes are also presented on the University of Hawaii's web site described in this volume by Harris and coworkers. The address for each site is as follows:

VolcanoWorld:	http://volcano.und.nodak.edu/
Michigan Technological University:	http://www.geo.mtu.edu/volcanoes/
NASA EOS Volcanology Team:	http://www.geo.mtu.edu/eos/
Real-time thermal monitoring:	http://volcano1.pgd.hawaii.edu/goes/

Where Next for Volcano Remote Sensing?

Several papers in this volume include discussions of missions that will fly in the next five years. As sensors with greater performance are flown on more spacecraft it is reasonable to expect that routine measurement for volcanoes in all parts of the world will be obtained. For example, data will be collected more frequently for tropospheric and stratospheric gas species of relevance to volcano monitoring, the collection of extensive digital topographic data, and an increase in the frequency and precision of measurements of volcanic thermal anomalies. Undoubtedly the volcanology remote sensing community will develop expertise in the uses of these observations, even though the sensors were not developed specifically for volcano studies. Rapid access to observations in near real-time will make these data of greater value for volcano hazard mitigation work, whether the risk is on the ground or in the air.

However, we can also envision possible future steps in volcano remote sensing. Certain key aspects of an active volcano will remain inaccessible to first-hand observation and yet be critical for understanding the eruption process or the changes in activity. For instance, no detailed data sets have been collected on the internal structure of an eruption plume. And yet, knowledge of the size, velocity and temperature distribution of clasts a function of three-dimensional position within a plume would dramatically improve our ability to model such events and to predict ash fall-out patterns and associated hazards such as the generation of pyroclastic flows (Sparks et al., 1997). A few experiments have been attempted using ground-based radar (e.g., Rose et al., 1995) but here it was the exterior of the plume that was being measured. Multi-wavelength radars that provide images at different depths beneath the optical surface could be developed. Such radars should preferably have a Doppler capability that enables the velocity of entrained particles to be measured (Seyfried and Hort, 1999). We know of no current plans to develop either a space-based or airborne example of such a radar system.

Integrated remote sensing studies of volcanoes can also be envisioned. Exciting new work by Harris et al. (1998) on the thermal monitoring of volcanoes indicates that magma production rates can be estimated. The next step in this approach might be the combination of these thermal observations with radar interferometry investigations (described in this volume by Zebker and colleagues) of the changes in a lava flow field to more accurately define the area of new lava. Topographic profiles collected via laser altimeters (Hofton et al., this vol.) could then be used to measure the thickness, and hence the volume, of these flows. Further insight of the productivity of the volcano could also be gained from measurements of the gas flux (Realmuto, this vol.) or the aerosols produced. To date, few studies have been conducted using the optical depth measurements of volcanic gas plumes such as the low altitude "vog" plumes produced by Kilauea volcano, Hawaii. Were time-series observations to be made under different viewing geometries (thereby measuring the optical phase function, from which the particle loading can be computed), then the flux of aerosols from a vent could be calculated and compared to the magma flux.

Finally, any future development in the remote sensing of active volcanoes must include a coherent plan for the routine collection and archiving of volcano data sets so that they can be easily accessed by the volcanological community. High resolution instruments such as ASTER, the Landsat 7 Enhanced Thematic Mapper, and the ENVISAT radar will not operate continuously due to power and on-board recorder limitations. The remote sensing community, in close collaboration with volcanologists, needs to develop a long-term acquisition plan comparable to the one for Landsat 7 (Goward et al., 1999), except specifically focused on monitoring volcanoes. Only in this way will the context measurements be available to describe the before-eruption conditions of the latest activity at a remote volcano.

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